Development of Film Actuator Operated by Magnetic Field for Micro-Machine

HIROMASA YABE AND YOSHITAKE NISHI

Department of Materials Science, TOKAI University,

1117 Kitakaname, Hiratsuka, Kanagawa, 259-1292 JAPAN

ABSTRACT: Fe-Pd alloy films, prepared by using a DC magnetron sputtering method, were developed as a high sensitive actuator, which was driven by the magnetic field. Fe-Pd alloy film shows large magnetostriction and high magnetostrictive susceptibility under 1 kOe. To evaluate the moving potential as magneto-driving actuator, the magnetostrictive properties were measured under different tensile loading stresses. Although the small tensile loading stress decreased the maximum value of magnetostriction, strong magneto-driving actuator of the Fe-Pd alloy film could be constantly operated by the magnetic field under larger loading stress for high magnetostrictive susceptibility.

INTRODUCTION

The response speeds of actuator materials are important factors for various applications. For example, the response speed of shape memory alloy (SMA; $\Delta\varepsilon/\Delta t$) is expressed by a following equation.

$$\Delta\varepsilon/\Delta t = d\varepsilon/dT \cdot dT/dt \qquad (1)$$

Here, $\Delta\varepsilon/\Delta t$ is dominated by the thermal expansion ($d\varepsilon/dT$) and the thermal conductivity (dT/dt). Generally, the thermal conductivity of Ti-Ni alloy is about 20 W/mK. Therefore, as for the movement speed of SMA is about maximum 100 Hz. On the other hand, the magnetic field has been expected as the stimulation without wiring work and high response speed over 10 MHz. Giant magnetostrictive materials (GMM) are one of representative actuator materials which operated by magnetic field. The response speed of GMM ($\Delta\lambda/\Delta t$) is expressed by a following equation.

$$\Delta\lambda/\Delta t = d\lambda/dH \cdot dH/dt \qquad (2)$$

Here, the response speed ($\Delta\lambda/\Delta t$) is dominated by the magnetostrictive susceptibility ($d\lambda/dH$) and the transmission speed of magnetic field (dH/dt). The transmission speed of magnetic field (dH/dt) is faster than that of the thermal conductivity (dT/dt). Thus, the high response speed ($\Delta\lambda/\Delta t$) of the GMM can be expected to be faster than that of the SMA. The responsiveness of the GMM is generally dominated by the magnetostrictive susceptibility. On the other hand, the magnetostrictive susceptibility ($d\lambda/dH$) is a controllable dominant factor for metallurgists by controlling morphology and alloy composition. In order to get the high response speed ($\Delta\lambda/\Delta t$) of the GMM, the high magnetostrictive susceptibility ($d\lambda/dH$) should be obtained. $Tb_{0.3}Dy_{0.7}Fe_2$ (Terfenol-D) was sensible actuator materials controlled by magnetic field (Clark, et al., 1975). The actuator, which was moved by magnetic field, enables to be the remote manipulation. Offering the advantages of lightweight, relatively simple design, and controllability by magnetic field, giant magnetostrictive films will be applied for sensitive remote actuators. To apply the electronic devices, mechanical devices and to improve the fatigue fracture, film thinning is useful method. Giant magnetostrictive $Tb_{0.3}Dy_{0.7}Fe_2$ films have been studied (Uchida, et al., 1996, Wada et al., 1996, Quandt et al., 1996). Recently, the giant magnetostrictive Fe-Pd alloy film, which shows high corrosion resistance and also shows high magnetostrictive

Corresponding Author: Yoshitake Nishi
E-mail; am026429@keyaki.cc.u-tokai.ac.jp

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susceptibility, has been studied (Yabe, et al., 2000). The $d\lambda/dH$ obtained was higher than that of the giant magnetostrictive $Tb_{0.3}Dy_{0.7}Fe_2$ thin film developed by Uchida et. al. on 1996 (Yabe, et al., 2003). However, in order to be applied for the new ferromagnetic film actuator in a practical design, the stress dependence of magnetostrictive susceptibility related to the responsiveness is a serious problem. Thus, the magnetostrictive susceptibility ($d\lambda/dH$) of the Fe-45at%Pd alloy film has been investigated, precisely. Therefore, the purpose of the present work is mainly to evaluate the stress dependence of magnetostrictive susceptibility ($d\lambda/dH$) of the high power Fe-45at%Pd film actuator.

EXPERIMENTAL PROCEDURE

Following methods carried out preparation and evaluation of the Fe-Pd actuator. To form the film of the fine columnar texture, a DC magnetron sputtering process was performed. Controlling the amount of Pd on the Fe target changed the chemical composition (Yabe, et al., 2003). The base pressure was less than 3.9 x 10^{-5} Pa and the leak rate was 5.0 x 10^{-7} Pa・m^3/s. The sputtering conditions were 6.0 x 10^{-2} Pa of Ar gas pressure with 200 W of DC sputtering power and 3600 s of sputtering time. The Fe-Pd film was deposited about 2μm in thickness on silicone substrate.

The film composition was analyzed by energy disperse X-ray spectroscopy (EDS; JSM-6301F, JEOL) as Fe-45.2 at%Pd eutectoid composition. The film crystal structure was analyzed by thin film X-ray diffraction (XRD; X'Part-MRD, PHILIPS). As a result of TF-XRD, the sample crystal structure shows face centered cubic (FCC). The strong X-ray peak of (111) plane was observed at each sample (Yabe, et al., 2000). The film texture was observed by means of field emission scanning electron microscopy (FE-SEM; JEM-6000 series WDS/EDS system, JEOL). The film morphology was a texture of fine columnar (Yabe, et al., 2000).

The magnetic property was measured by a vibrating sample magnetometer (VSM; Model BHV-55, RIKEN). VSM I-H curve show small hysteresis and strong plane anisotropy of magnetization (Yabe, et al., 2003). The in-plane magnetostriction ($\lambda_{//}$) of film was measured by a cantilever method and was estimated by following equations (Yabe, et al., 2003).

$$d = lD / 2L \qquad (3)$$

$$\lambda_{⫽} = d \cdot t_s^2 \cdot E_s / 3t_f \cdot \ell^2 \cdot E_f \qquad (4)$$

Here t_s and t_f were the thickness values of silicon substrate and film, respectively. d and ℓ were the bending distance of the sample and the distance of clamp and spot of laser on film, respectively. E_s and E_f were the Young's modulus of silicon substrate and Fe-45at%Pd film as E_s= 171.6 GPa and E_f= 87.3 GPa, respectively (Yabe, et al., 2003). The Young's modulus was measured by a nano-indenter method (nano-indenter;ENT-1100a, ERIONIX).

RESULTS AND DISCUSSIONS

Stress dependence of Magnetostriction

The in-plane magnetostriction ($\lambda_{//}$) of the film was obtained from measurements of the bending of a rectangular cantilever consisting of the film and substrate. All film devices were saturated in the applied magnetic field of 1 kOe. The $\lambda_{//}$-$H_{//}$ curve of the Fe-Pd alloy films show high magnetostrictive susceptibility in low magnetic field (Yabe, et al., 2003).

One serious obstacle to applying such a bi-metal as a practical wireless actuator is its stress dependent magnetostriction yielded by the magnetic field. To evaluate the stress dependence, the magnetostriction was measured at different loading stresses. The tensile stress dependence of magnetostriction in Fe-45at%Pd bi-metal was measured (Yabe, et al., 2001, 2002, 2003). In order to estimate the magnetostriction of the Fe-45at%Pd alloy film on the silicone substrate, the tensile loading stress on film (σ_f) was calculated by a following equation.

$$\begin{aligned} \sigma_f &= E_f \cdot \varepsilon \\ &= E_f \cdot (\sigma_{all} / E_{all}) \end{aligned} \qquad (5)$$

Here, ε was strain induced by tensile loading. σ_{all} was the overall tensile stress of sample. Overall Young's modulus of sample E_{all} is expressed by following equation (6).

$$E_{all} = E_f \cdot A_f / A_{all} + E_s \cdot A_s / A_{all} \quad (6)$$

Here, A_f , A_s and A_{all} were cross sectional area of film, substrate and overall, respectively. Therefore, σ_f was expressed by a following equation (7).

$$\sigma_f = E_f \cdot (P_{all} / (A_{all} \cdot E_{all})) \quad (7)$$

Here, P_{all} was overall load.

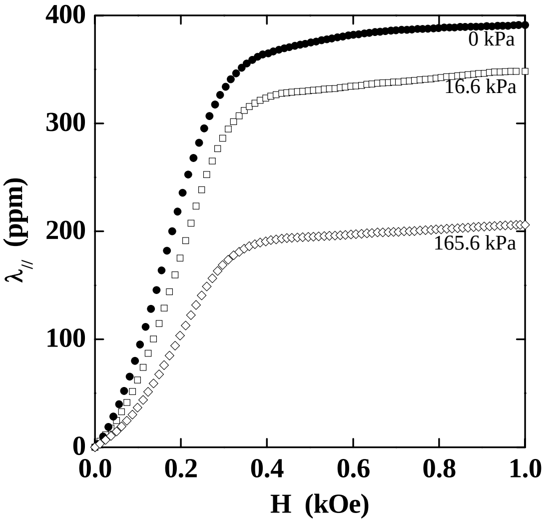

Figure 1. *The relationship between applied magnetic field (H) and the magnetostriction ($\lambda_{//}$) of Fe-45at%Pd alloy film at different loading stresses. In this figure, the plots show the magnetostriction of test device under different loading stresses of unloaded, 16.6 and 165.6 kPa; these plots are denoted using closed circles, open squares, open triangles, open turned triangles, open diamond and open circles, respectively.*

Figure 1 shows the relationship between the applied magnetic field ($H_{//}$) and the magnetostriction ($\lambda_{//}$) of Fe-45at%Pd alloy film at different loading stresses. The applied magnetic field drastically enhanced the magnetostriction of all loaded samples for below 0.4 kOe. With the tensile loading stress getting large, the magnetostriction decreased. The 165.6 kPa-loaded magnetostriction at 1 kOe was about half value for unloaded magnetostriction. These results obtained suggest that a large magnetostriction was generated in the bi-metal constructed by Fe-45at%Pd alloy film and silicone substrate. The magneto-driving Fe-Pd alloy film actuator could be operated by applied magnetic field from earth magnetic field to 1 kOe under large loading stresses.

Stress dependence of magnetostrictive susceptibility

Another potential obstacle is actuator response time. To evaluate the load dependent response speed of the new actuator, the magnetostrictive susceptibility ($d\lambda/dH$) was obtained at different tensile loading stresses. The magnetostrictive susceptibility ($d\lambda/dH$) was calculated by the differential values of the magnetostriction quantity in the applied magnetic fields.

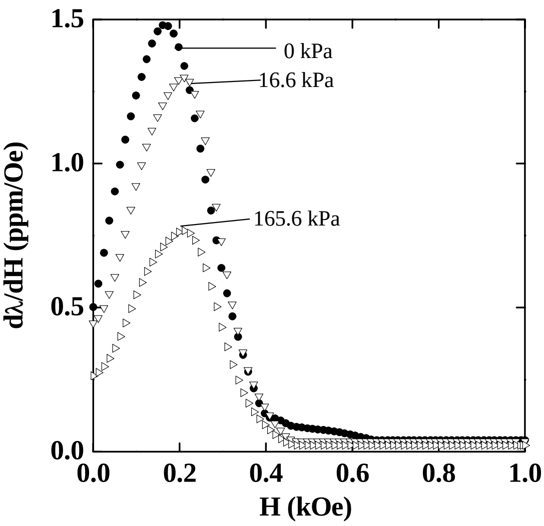

Figure 2. *The relationship between the applied magnetic field (H) and the magnetostrictive susceptibility ($d\lambda/dH$) of the Fe-45at%Pd alloy film at different loading stresses. In this figure, the plots show the magnetostrictive susceptibility of test device under different loading stresses of unloaded, 16.6 and 165.6 kPa; these plots are denoted using closed circles, open squares, open triangles, open turned triangles, open diamond and open circles, respectively.*

Figure 2 shows the relationship between the applied magnetic field (H) and the magnetostrictive susceptibility ($d\lambda/dH$) of the Fe-45at%Pd alloy film at different loading stresses. The H below 0.16 kOe increased the magnetostrictive susceptibility for unloaded sample. The maximum value of $d\lambda/dH$ was found at 0.16 kOe. The loading stress dependent relationships between $d\lambda/dH$ and H were also observed. The tensile loading stress decreased the maximum value of $d\lambda/dH$. Furthermore, the tensile loading stress also increased the H at the maximum peak value of $d\lambda/dH$-H curves. An initial stage of magnetostriction is usually caused by easy mobile factors acted by weak magnetic field. If the tensile loading stress prevents to move the factors, decreasing the maximum $d\lambda/dH$ value and increasing the H at the maximum $d\lambda/dH$ value against loading can be explained.

CONCLUSION

A new high responsiveness wireless actuator, driven by the magnetic field of Fe-45at%Pd alloy film on a silicone substrate, was prepared by using a DC magnetron sputtering process. A large magnetostriction was induced by the magnetic field under a large tensile loading stress. The maximum value of magnetostrictive susceptibility was found at 0.16 kOe. Although the small tensile loading stress decreased the magnetostrictive susceptibility a strong magneto-driving actuator of the Fe-45at%Pd alloy film could be constantly operated by the small magnetic field under larger loading stress

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